AN EXPERIMENTAL STUDY OF FREQUENCY MODULATION OF THE LASER BY THE ZEEMAN EFFECT

By

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Major Department: Electrical Engineering

The purpose of this experimental study is to explore the use of the Zeeman effect to frequency modulate a gas laser for communication purposes. Lasers are used with mirrors outside the discharge tube and within it, and with axial and transverse magnetic fields from zero to seventy gauss. The laser is a helium-neon type with confocal mirrors, operating at 6328 Å. No experiments involving the Zeeman effect for modulation in either internal or external mirror gas lasers have been reported in the literature, and it is believed that these are original.

Neon is excited in the laser discharge tube to a metastable state from which laser action at 6328 Å may occur. A resonant cavity formed by multiple dielectric mirrors at

each end of the discharge tube reflects radiation necessary to stimulate other neon atoms in the metastable state to emit. In the resonant cavity, an integral or half-integral number of light wave lengths may be maintained. For a mirror separation of 128 centimeters, the frequency difference between standing waves of visible light, or axial modes, is 117 mcps.

The Zeeman effect is a splitting of an energy level into sublevels in the presence of a magnetic field, resulting in splitting of the corresponding spectral line. The light viewed parallel to the field axis contains the σ^+ and σ^- beams, which are circularly polarized. By modulating the field, the frequency difference between the σ^+ and σ^- beams will be modulated, making frequency modulation possible. The receiver is a photomultiplier tube whose photocathode has a square law characteristic which makes detection possible. Several peculiarities exist when using the Zeeman effect to frequency modulate this type of laser, including linear polarization of the light and frequency pulling due to the optical cavity.

The study was made using PEK LT-11 and LT-12 laser tubes, Optics Technology, Inc., mirrors, and an internal mirror laser built in the laboratory. Preliminary tests for excitation power, beam display and mirror alignment were made.

The LT-11 laser tube was used with external mirrors,

Brewster-angle windows, and an axial magnetic field. The Zeeman effect could not be detected, although the axial mode beats and the transverse mode beats were detected. Similar results were obtained with the LT-12 tube with external mirrors, Brewster-angle windows, and a transverse magnetic field. It is concluded that strong polarizing action of the Brewster-angle windows prohibits or greatly diminishes the Zeeman effect.

The internal mirror laser with a transverse magnetic field exhibited the Zeeman effect with the field applied, as well as the transverse and axial mode beats. A field of sixty gauss gave a $\sigma^+ - \sigma^-$ line splitting of 1000 cps which was then modulated over a frequency range of 20 to 200 cps and received. It was concluded that this system is useful for narrow-band, economical signal transmission by laser beam.

I

INTRODUCTION

Since the time of the mathematical description of the laser, or optical maser, by A. L. Schawlow and C. H. Townes [1], the variety of applications of the laser has grown almost as rapidly as the number of speculations on its possible uses. The purpose of this research was to study experimentally the frequency modulation of a gas laser by means of the Zeeman effect. The gas laser was chosen over the ruby and the junction diode lasers for its narrow line width, continuous wave operation, and lack of special temperature requirements.

Frequency modulating of the laser by the Zeeman effect would offer a simple, economical communication system. The modulator would be simple and economical to construct, and the receiver would be no more complicated than f-m receivers presently used at radio frequencies.

The study was made using sealed laser discharge tubes with Brewster-angle windows and external mirrors, and also with demountable discharge tubes with internal mirrors, normal windows, and a gas-filling apparatus.

Experiments with a magnetic field applied to the gas laser with external mirrors have not been reported in the literature. Also, modulation of an external magnetic field

passing through an internal mirror gas laser, and design and operation of an f-m receiver of the type used have not been reported. It is believed that this work is original.

II
PHYSICAL PRINCIPLES

The Laser

Laser is an acronym for light amplification by stimulated emission of radiation. In nearly all cases the light amplifier has sufficient positive feedback to make it behave as an oscillator or generator. The helium-neon laser, the most common form of gas laser, uses an electrical discharge to excite the helium atoms. In several of its transitions back to the ground state, the helium atom gives up internal energy directly to the neon atom in a collision, rather than by radiation. Several of the energy levels to which the neon atom may be excited are metastable. If radiation corresponding to a downward transition from a neon metastable state to a lower excited state or to the ground state interacts with another metastable neon atom, the atom can radiate by stimulated emission, in addition to spontaneous emission. The laser tube is fitted with high reflectance mirrors at each end of the tube so that this radiation builds up in intensity.

The laser to be discussed here is the gas laser, specifically the helium-neon laser. The essential parts are: a sufficient number of atoms whose electronic energies can

be raised to a metastable state so that a population inversion will occur; a means of exciting these atoms; and a high frequency optical cavity which will support standing waves at a frequency corresponding to a desirable downward transition.

Stimulated Emission of Radiation

Schawlow and Townes [1] have discussed the theory of the laser and have shown that there are two requirements for amplification by stimulated emission. These are: a population inversion between the electronic states involved in the laser operation and a radiation power gain due to this population inversion which is equal to the sum of all power losses.

Population inversion is necessary if there is to be an increase in, or amplification of, the energy density of the radiation passing through an active laser medium. We consider for simplicity a system in which there are only two electronic energy levels. There are three processes pertaining to electronic energy jumps of atoms between these two states and radiation of a frequency, f, corresponding to the energy difference between these two states. The first process is absorption of energy in the radiation resulting in an increase in electronic energy equal to $W_m - W_n$, where W_m is the energy of the higher energy state, m, and W_n is that of the lower state, n. The number of atoms making this jump per unit of time equals $N_n u_{mn} B_{nm}$, where u_{mn} is

the energy density of the radiation and B_{nm} is the Einstein coefficient for absorption.

The other two processes are emission processes. One is stimulated or induced emission which corresponds to stimulated or induced absorption discussed above. This is a direct interaction with the radiation, in which the photons emitted have a constant phase relationship with the radiation, adding to the energy density. The number of atoms making this emissive jump per unit time equals $N_m u_{mn} B_{mn}$, where N_m is the number of atoms in the state m. The Einstein coefficient B_{mn} will be shown to equal B_{nm} in the discussion of the two state system below. The second emission process is spontaneous emission; the number of atoms making this emissive jump equals $N_m A_{mn}$. Note that no radiation field is necessary for the spontaneous emissive jump.

If the two state system described above is in thermodynamic equilibrium with the radiation field, the population of each state is constant. Then

$$N_n B_{nm} u_{mn} = N_m B_{mn} u_{mn} + N_m A_{mn}. \qquad 1.$$

In equilibrium, $N_m < N_n$ unless A_{mn} is zero. According to the Boltzmann distribution,

$$\frac{N_m}{N_n} \doteq \frac{g_m}{g_n} \frac{e^{-kT/W_m}}{e^{-kT/W_n}} \qquad 2.$$

where g_m and g_n are the statistical weights of the two states, k is the Boltzmann constant, and T is absolute temperature. If g_m and g_n are equal, then $N_m < N_n$.

Assuming g_m equals g_n and that $N_m A_{mn} << N_m B_{mn} u_{mn}$, if $N_m > N_n$, amplification of the radiation of energy density, u_{mn}, will take place. This is because more atoms are stimulated to emit in a jump from m to n than are induced to absorb in a jump from n to m, or

$$N_m B_{mn} u_{mn} > N_n B_{nm} u_{mn} \qquad 3.$$

The number of n-m transitions is

$$N_n B_{nm} u_{mn}\ dt$$

and the absorbed energy is

$$dW_{ab} = N_n B_{nm} u_{mn}\ h\ f_{mn},$$

where h is Planck's constant. Similarly, the number of stimulated m-n transitions is

$$N_m B_{mn} u_{mn}\ dt$$

and the emitted energy is

$$dW_{em} = N_m B_{mn} u_{mn}\ h\ f_{mn}\ dt.$$

The net emitted energy rate, or power, is

$$\frac{d}{dt}(W_{em} - W_{ab}) = (N_m - N_n)\ B_{mn} u_{mn}\ h\ f_{mn}. \qquad 4.$$

Obviously $\frac{d}{dt}(W_{em} - W_{ab})$ is positive only if $N_m > N_n$. This net emitted power is evidenced in an increased u_{mn}.

At this point, it is noted that as T approaches infinity,

$$\frac{e^{-kT/W_m}}{e^{-kT/W_n}} \rightarrow 1$$

For g_m equal to g_n,

$$\frac{N_m}{N_n} \to 1$$

Also, $u_{mn} \to \infty$.

Then

$$\frac{A_{mn}N_m}{B_{mn}u_{mn}N_m} \to 0$$

and

$$B_{mn} = B_{nm} \qquad 5.$$

as asserted earlier. Since B_{mn} and B_{nm} are microscopic in nature and are not temperature dependent, this equality holds for all values of T. By substituting the exponential ratio of N_m/N_n in equation 1 ,

$$u_{mn} = \frac{A_{mn}/B_{mn}}{e^{hf/kT}-1} \quad .$$

Comparing this with the Planck radiation formula,

$$u_f df = \frac{8\pi f^2}{c^2} \; \frac{hf}{e^{hf/kT}-1} \; df$$

where c is the speed of light and df is a small band of frequencies about f, the following equation is obtained:

$$A_{mn} = \frac{8\pi f^2}{c^2} \, hf \; B_{mn} \; .$$

Now the energy lost in the spontaneous m-n transitions may be calculated relative to the energy added to u_{mn} by stimulated emissions.

The second requirement is that the power gain achieved above and described in equation 4 equal the sum of power

losses in the total radiation system of the laser; except of course, for absorption, already accounted for. These losses occur in the mirrors, in the windows which may be in the basic system, in non-active gas, and in dispersive media.

In the laser used in this experiment, the discharge tube was filled with a mixture of about ten parts of helium to one part neon, to a total pressure of one micron. An electrical discharge excites the helium to a number of different energy states. The helium decays back to the ground state by means of a number of transitions, usually emitting radiation spontaneously with each transition. There are several inelastic collisions in which electronic excitation energy is exchanged between helium and neon atoms. These include:

$$\begin{aligned} He(2^1S) + Ne(^1S_0) &\rightarrow He(^1S_0) + Ne(3s_2) \\ He(2^3S) + Ne(^1S_0) &\rightarrow He(^1S_0) + Ne(2s_2) \end{aligned} \qquad 6.$$

In each of these collisions the neon is excited to a metastable state from which stimulated emission can take place. From the lowest energy electronic state, 2p, neon atoms decay rapidly to the ground state by spontaneous emission. The Grotrian diagram of energy levels for this cycle, beginning with helium in the excited state, is given on the next page in Figure 1.

In this figure, the dotted line indicates the collision described by the first part of equation 6 and the solid line indicates the collision described by the second part

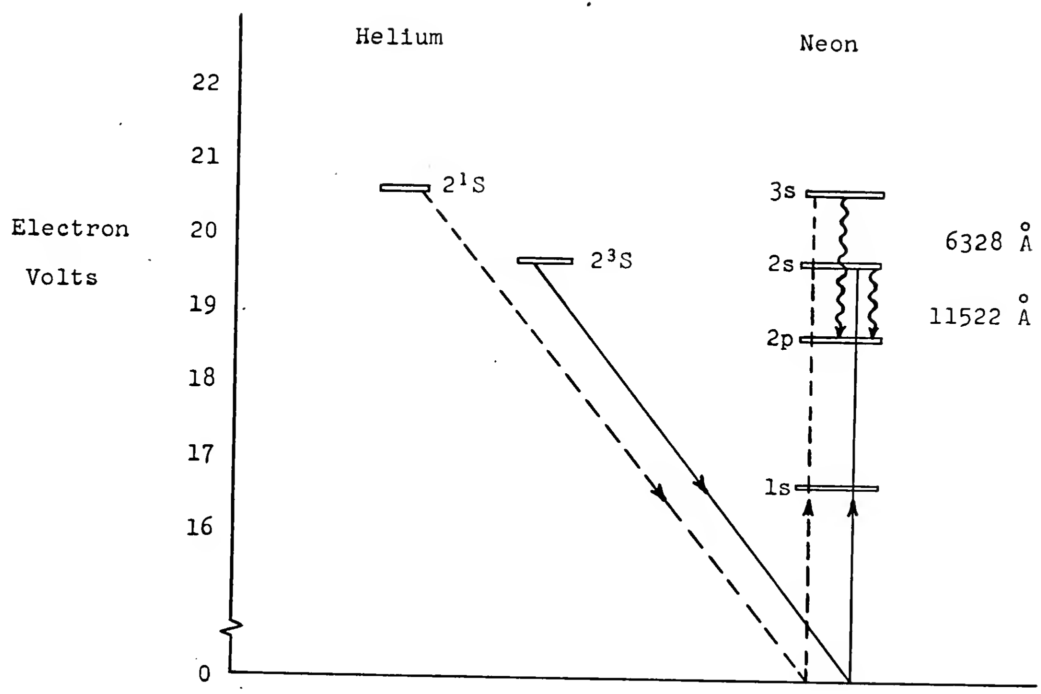

Figure 1. Grotrian Diagram for Helium and Neon Levels Pertinent to the Laser

of equation 6. Stimulated emission due to the downward transition from each neon metastable state is indicated by a wavy line; the emission wavelength is also given. The rapid decay time for the Ne(2p) energy level permits the necessary population inversion between this state and the metastable 3s and 2s states.

Optical Configuration

The stimulated emission described above must reflect back and forth in the laser tube to stimulate more emission. The gain per pass is small; an attenuation of two to three per cent could stop the laser operation. Therefore, mirrors used must have very high reflectance. Typical values of the reflectance for gas lasers are 99.0 to 99.5 per cent. Of the remaining .5 per cent of the light beam, probably 0.3 per cent is absorbed and 0.2 per cent transmitted. Mirrors commonly used in laser applications have nine to thirteen layers of dielectric coatings, usually with two different dielectrics alternating, which are applied in precise thicknesses to substrates whose surfaces are controlled to one tenth wave length or better. The surface may be flat or curved for optical configurations of parallel plane, confocal, spherical or combination mirror systems [2,3]. Several configurations are shown on the next page as Figure 2 [1,3].

The confocal mirror configuration was used in this experimental study for both the internal and external mirror lasers. The mirrors, produced by Optics Technology, Inc.,

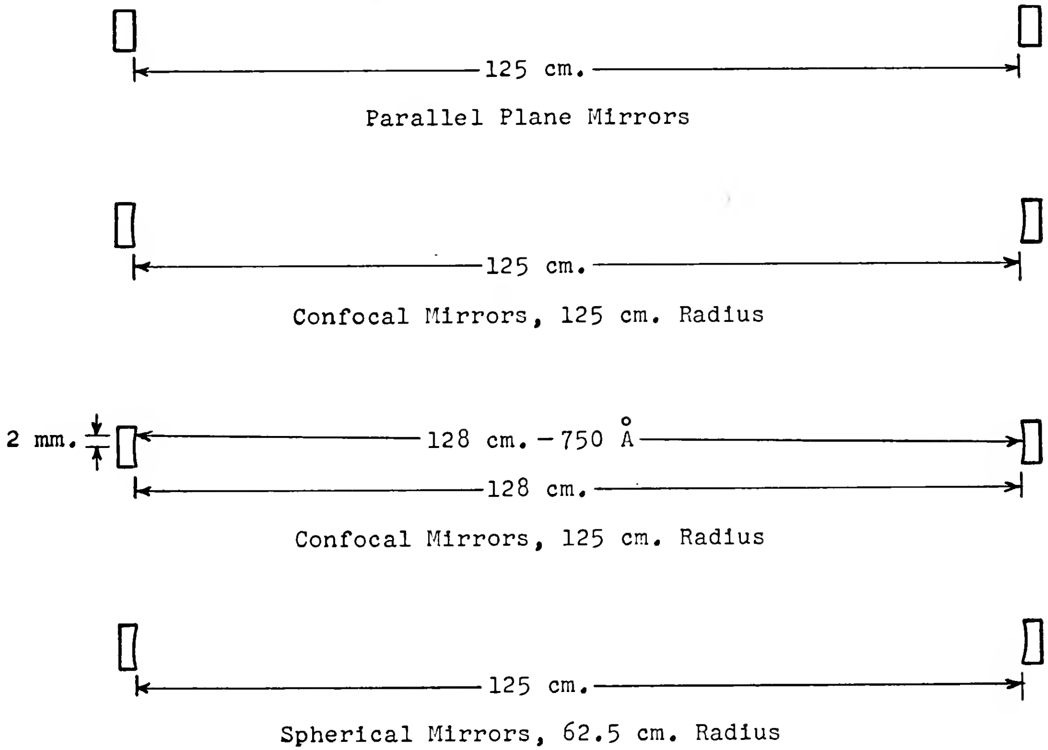

Figure 2. Laser Mirror Configurations

are shaped for a nominal separation of 125 centimeters and are multiple dielectric coated. The PEK laser tubes required that the mirrors be external. Later investigations required that internal mirrors be mounted on a laser tube built by the author. The external mirrors are victims of atmospheric dust, the internal mirrors are subject to electron and ion bombardment during operation; each of these effects decreases reflectivity.

A laser with external mirrors and Brewster-angle windows is shown on the next page in Figure 3. Brewster-angle windows [4] are used because incident radiation which has its electric vector parallel to the plane of incidence suffers no reflection. A laser with internal mirrors is shown in Figure 4 on page 14.

The Zeeman Effect

Excited atoms may be in a degenerate energy level. If such atoms are placed in a magentic field, this degeneracy (in general) is removed; the excited energy level splits into a number of sublevels. If the spectrum of transitions between the two levels is observed, what had been a single line now becomes several individual lines. This is the Zeeman effect [4]. For the hydrogen atom, the number of sublevels is determined simply by the quantum number m. As the number of electrons in an atom increases the number of sublevels and the system of energy coupling between the electrons

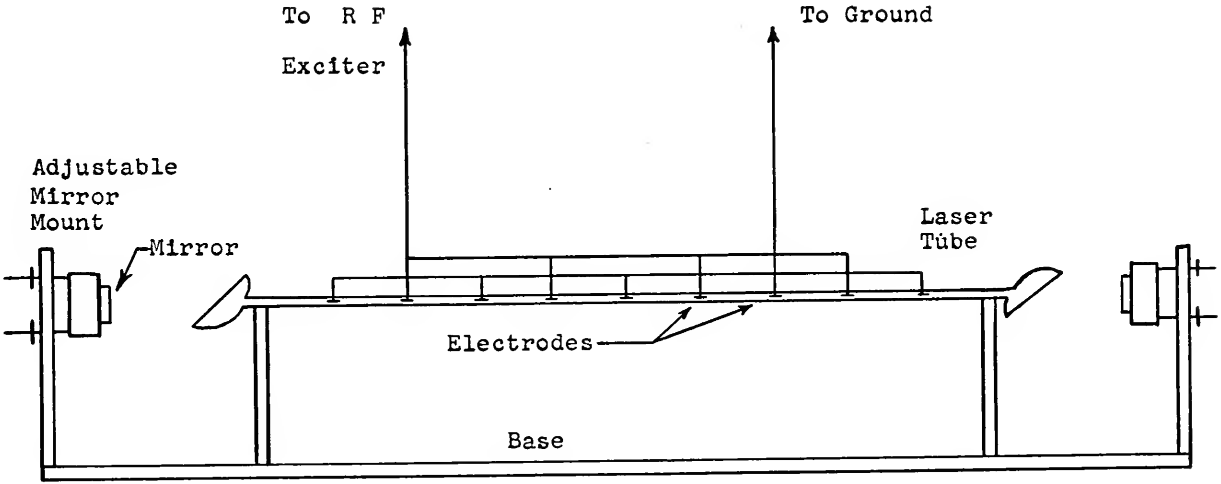

Figure 3. Laser with External Mirrors

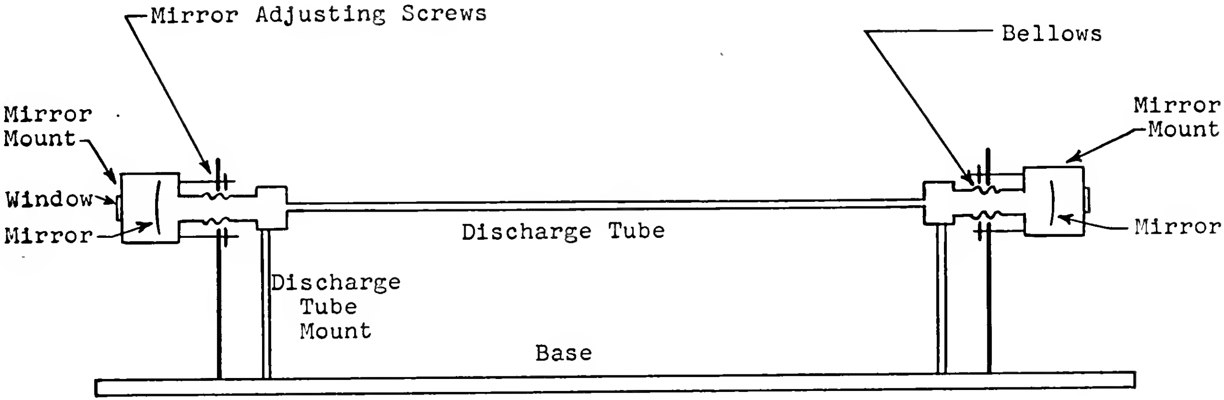

Figure 4. Laser with Internal Mirrors

becomes complicated. In their paper, Statz, Paananen, and Koster [5] suggest that j-l coupling be used for neon. This is also called Racah or extreme coupling. Knowledge of the coupling was used to determine the Landé-g factor, which, in turn, was used to determine the splitting of the levels. Statz, et al. [5] calculated $g = 1.33$ for the $2s_2$ state, used the value of 1.3 for the $2p_4$ state, and quoted the experimental value for the $3s_2$ state as 1.295. The dominant stimulated neon transition in the visible spectrum is the $3s_2$-$2p_4$ transition, for which a Landé-g of 1.3 will be used.

Removal of the energy level degeneracy by placing the two state system previously discussed in a magnetic field makes possible emissive transitions from one or more sublevels in state m to one or more sublevels in state n. The energy separation among the sublevels of m and among the sublevels of n is quite small compared with the m-n transition emitted energy. This variation in the m-n transition energy may be calculated by the quantum mechanical first order perturbation theory. The energy differences among the sublevels is interaction energy, between the magnetic moment of the atom, denoted by $\underline{u}$, and the magnetic flux density $\underline{B}$ of the applied field.

$$W = -\underline{u} \cdot \underline{B} \qquad 7.$$

The theories for L-S coupling are most widely used and will be summarized here to demonstrate the dependence of the interaction energy W on the Landé-g factor. A g factor

based on j-l coupling rather than L-S coupling will then be used.

The net magnetic moment $\underline{u}$ is the vector sum of the orbital magnetic s_i of all v electrons of an atom.

$$\underline{u} = - \sum_{i=1}^{v} [\frac{1}{2} (\frac{e}{m}) \underline{li} + \frac{e}{m} \underline{si}]$$

$$= - \frac{1}{2} (\frac{e}{m}) (\underline{L} + 2\underline{S})$$

$$= - \frac{1}{2} \frac{e}{m} (\underline{J} + \underline{S})$$

where $J = \underline{L} + \underline{S}$

Then

$$W = \frac{1}{2} \frac{e}{m} (\underline{J} + \underline{S}) \cdot \underline{B}.$$

From a consideration of the vector quantities and their various rates of precessing, the following equations are developed:

$$W = \frac{1}{2} \frac{e}{m} \frac{[(\underline{J} + \underline{S})\cdot\underline{J}] [\underline{J}\cdot\underline{B}]}{|J^2|}$$

$$W = \frac{1}{2} \frac{eB}{m} \frac{[|\underline{J}|^2 + \frac{1}{2}(|\underline{J}|^2 + |\underline{S}|^2 - |\underline{L}^2|)] J_z}{|\underline{J}^2|}$$

where $J\cdot S = \frac{1}{2}(|\underline{J}|^2 + |\underline{S}|^2 - |\underline{L}|^2)$. The quantum mechanical operator for the interaction energy, W, is just the operator for the quantity in the right hand member of the above equation. The shift in the energy of a quantum state specified by the quantum numbers L, S, J, and M_J is, according to first order perturbation theory, given by

$$W = \frac{1}{2} \frac{eB}{m} [1 + \frac{J(J+1)+\frac{1}{2}[J-(J+1)+S(S+1)-L(L+1)]}{2J(J+1)}] M_J\hbar.$$

$$W = \frac{1}{2}\,\frac{e\hbar B}{m}\,g\,M_J \qquad 8.$$

where g has the value of the quantity in large brackets in the preceeding equation.

The energy differences become

$$\Delta E_m = \frac{1}{2}\,\frac{e\hbar B}{m}\,g_m\,M_{Jm} \text{ and}$$

$$\Delta E_n = \frac{1}{2}\,\frac{e\hbar B}{m}\,g_n\,M_{Jn}\ . \qquad 9.$$

The levels and transitions involved in the two state system are depicted below, along with the resultant spectral lines. The system with g_m equal to g_n exhibits a "normal" type of Zeeman effect, though with an abnormal line separation unless the g factors equal one. The system with g_m unequal to g_n exhibits the anomalous Zeeman effect.

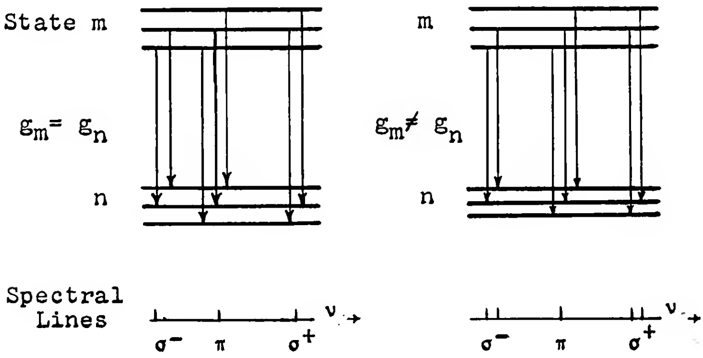

Figure 5. Energy Levels and Spectral Lines of the Zeeman Effect

The radiation emitted by the atoms is not uniform spatially. The emission of the σ and π components of the radiation is governed by quantum selection rules, the results of which are indicated below in Figure 6.

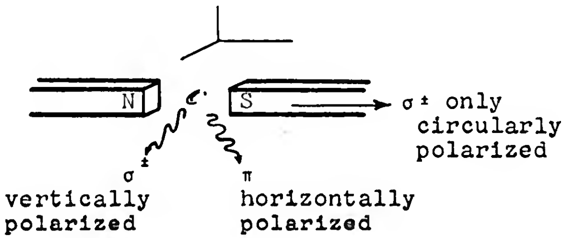

Figure 6. Emission Pattern Due to the Zeeman Effect

Fundamentals of Frequency Modulation

Frequency modulation is a means of modulating the carrier with a signal such that the frequency of the carrier deviates from its center frequency a number of times per second which is equal to the frequency of the signal, and deviates a number of cycles per second from the center frequency according to the amplitude of the signal. Expressed mathematically [6] for a carrier of amplitude A and a signal frequency of the form $B \sin \omega_s t$, the frequency modulated signal is

$$A(t) = A \sin (\omega_c + m B \sin \omega_s t)t \qquad 10.$$

where ω_c is the center frequency of the carrier and m is the modulation index.

Phase modulation is similar to frequency modulation

except that the phase of the carrier is changed according to the signal, or

$$A(t) = A \sin (\phi_c + m_p B \sin \omega_s t)$$

$$= A \sin (\omega_c t + m_p B \sin \omega_s t)$$

where $\phi_c = \omega_c t$. To relate phase modulation to frequency modulation, the parenthetical part of the above equation is differentiated with respect to time to obtain $d\phi/dt$, or frequency, to compare with equation 10.

$$\frac{d}{dt} (\omega_c t + m_p B \sin \omega_s t) = \omega_c + m_p B \omega_s \cos \omega_s t$$

If, before the modulation took place, the signal were integrated, it would be of the form

$$\int B \sin \omega_s t \, dt = - \frac{1}{\omega_s} B \cos \omega_s t.$$

Replacing the signal with its integral in the derivative above,

$$\frac{d}{dt} (\omega_c t - m_p B \frac{1}{\omega_s} \cos \omega_s t) = (\omega_c + m_p B \sin \omega_s t). \qquad 11.$$

Equation 11 now has the same form as the parenthetical part of equation 10. Therefore, given a phase modulation device, frequency modulation will result if the signal is first integrated. Since a frequency modulated signal may be obtained, several means of phase modulation will be discussed.

In applying the laser to communications work, information must be put on the beam of light using either amplitude or frequency modulation. Here, amplitude modulation includes most forms of pulse modulation and frequency modulation includes phase modulation. Only frequency modulation will be

considered here.

Methods of Frequency Modulation

There are at least four methods of frequency modulating the laser beam. The first, the subject of this paper, employs the Zeeman effect. This method will be discussed in greater detail in the next section. The second uses an electromechanical transducer to vary the position of one of the high reflectance mirrors [7]. This gives a Doppler shift to the light reflected and a change of optical cavity frequency. This motion is

$$Z = Z_o + k\ B \sin \omega_s t \qquad 12.$$

where k is the transducer coefficient, Z is the mirror separation, and $B \sin \omega_s t$ is the signal. For a constant mirror displacement

$$Z = Z_o + a$$

there will be a change in the cavity frequency, but no Doppler shift. The result of changing the optical cavity frequency is discussed in Chapter III.

The third method makes use of an electro-optic material, that is, a material in which the velocity of light in the z direction is a function of the voltage applied in the y direction. Two such materials, which are crystalline, are ammonium dihydrogen phosphate, ADP, and potassium dihydrogen phosphate, KDP. This method involves placing one of these crystals in the optical cavity [8]. This changes the

velocity of light in the cavity, giving a Doppler shift to the light frequency and a change of optical cavity frequency. The fourth method uses the ADP or KDP crystal outside the optical system, where the output beam will pass through it [9]. This gives only a Doppler shift to the light frequency, but has the advantage of no added item within the optical system of the laser oscillator, which could cause diffraction or attenuation of the beam, possibly stopping oscillation.

Details of Frequency Modulation by the Zeeman Effect

Unlike the second, third and fourth methods just listed, the first method of frequency modulation by the Zeeman effect is achieved directly--phase modulation by Doppler shift is not an intermediate process. From the discussion of the Zeeman effect, the following equations are obtained:

$$W = E_m - E_n$$

and

$$\Delta W = \Delta E_m - \Delta E_n = \frac{1}{2}\,\frac{e\hbar B}{m}\,(g_m M_{Jm} - g_n M_{Jn})$$

A quantum selection rule states that $M_{Jn} = M_{Jm} + 1$, M_{Jm}, $M_{Jm} - 1$. The σ spectral lines are due to M_{Jn} not equal to M_{Jm}. Assuming that g_m equals g_n and M_{Jn} equals $M_{Jm} - 1$, then

$$\Delta W = \frac{1}{2}\,\frac{ehB}{m}\,g = g\mu_H B$$

The frequency difference between the σ and π rays is given by the following equation

$$F = g\mu_H B/\hbar.$$

Finally

$$f/B = g\ 1.4 \text{ mcps} \qquad 14.$$

where f is the difference between the π ray frequency and the σ ray frequency, B is the magnetic field strength, g is the Landé-g factor, μ_H is the magnetic moment component in the direction of the applied H field, and h is Planck's constant. This assumes that $g_J = g_{J+1}$. From both experiment and theory, the Landé-g factor is known to be approximately 1.3 for transitions of interest in this work.

For the general case, which produces the external magnetic field, let the coil be excited by a current which is

$$I(t) = I_0 + I_s \sin \omega_s t \qquad 15.$$

where I_0 is a constant or bias current and $I_s \sin \omega_s t$ is the signal. With a proportionality constant k' relating the current I(t) to the flux density B(t), the frequency expression becomes

$$f = 1.3(1.4)\ k'\ (I_0 + I_s \sin \omega_s t) \text{ mcps}. \qquad 16.$$

With I_0 equal to zero, the center frequency of the light beam will be the same as the frequency for zero magnetic field. Figure 7 is a plot of the beam frequencies for a certain input.

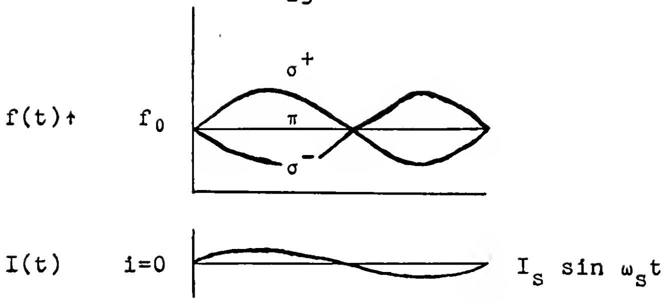

Figure 7. Spectral Lines as a Function of Current

With circular polarizers it may be possible to separate the σ^+ and the σ^- beam components. Otherwise the signal may be lost or may be recoverable only with a large second harmonic component.

With I_0 greater than $|I_s \sin \omega_s t|$ the center frequencies will be shifted away from the zero field frequency. Figure 8 is a plot of the beam frequencies.

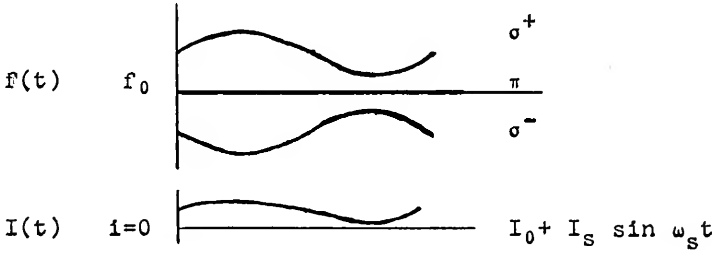

Figure 8. Spectral Lines as a Function of Current

The beam components now have a definite separation and may lend themselves to considerably simpler detection techniques. In Figures 7 and 8, the π component is included, although, under certain conditions to be described, it will not be in the output beam.

III

THE ZEEMAN EFFECT FREQUENCY MODULATED LASER

The physical principles pertinent to the laser which is frequency modulated using the Zeeman effect have been discussed. Certain operational peculiarities appear when a magnetic field is applied to a laser. These will now be discussed with emphasis on the helium-neon laser operating at 6328 Å with external mirrors and Brewster-angle windows on the discharge tube. Several experiments performed by others, which are concerned with the Zeeman effect and some of the peculiarities will be discussed also. Finally, a means of receiving the light signal will be described.

A transmitter consisting of a laser with its modulator and a receiver are needed for a one-way communication system. The simplified system shown in Figure 9 on the next page is similar to the actual system which was constructed for this experiment, described in the next chapter. The simplified system is reminiscent of the system employing a reflex klystron in the transmitter, where signal voltage is merely applied to the klystron reflector and a frequency modulated signal is obtained.

The Light Beam Transmitter

The laser with the magnet is the essential part of

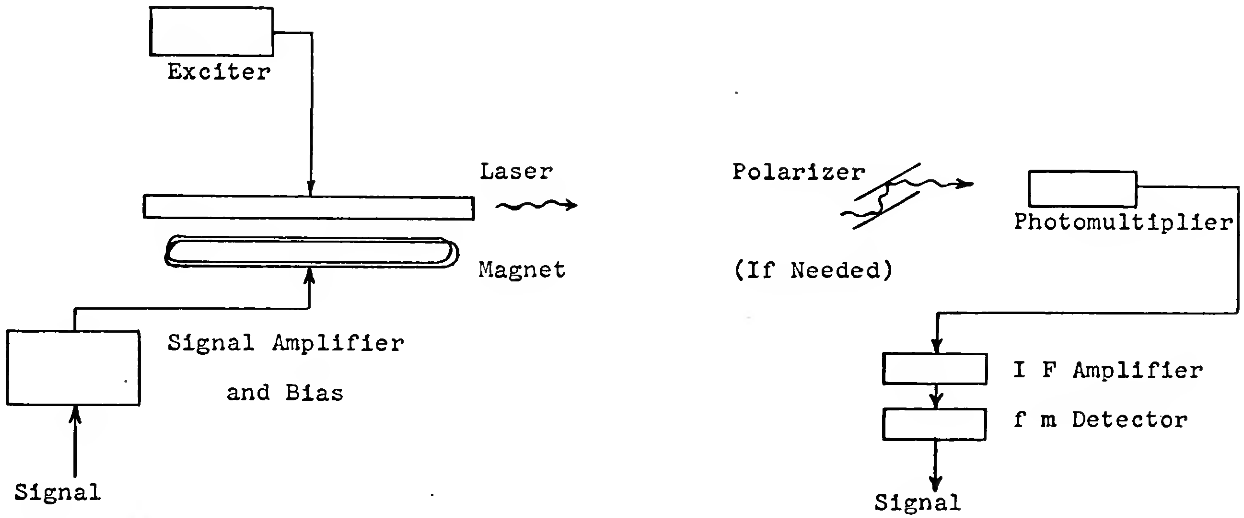

Figure 9. Sample One-Way Laser Communication System

the transmitter. The transmitter performance is affected by the discharge tube configuration, the optical configuration, and by "frequency pulling." These three factors will now be discussed.

Discharge Tube Configuration

The discharge tube may have the mirrors built in, or it may be constructed for use with external mirrors. In either case, there are windows at each end of the tube through which the beam passes. These windows must be optically flat if the wave front is to be undistorted. As discussed in the chapter on physical principles, Brewster-angle windows are commonly used for the external mirror configuration, since they permit the electrical field vector to pass through in one polarization without reflection. This means that the beam which builds up within the cavity is linearly polarized; so, also, is the output beam. If internal mirrors are used, the windows are usually perpendicular to the axis to avoid a polarizing effect.

An axial magnetic field applied to a laser will split the energy levels as shown in Figure 5 on page 17. Based on the calculations in the section on the Zeeman effect, the Landé-g factors for the initial and final states are assumed to be 1.3. The spectral line simplicity (but not the spacing) of the normal Zeeman effect will be observed. If the laser has internal mirrors and perpendicular windows, the axial field will cause the output beam to split and be

made up of two components, the σ^+ and σ^- circularly polarized rays. As the π ray does not exist in the axial direction, there will be no stimulation for the transition which produces the π ray.

An axial magnetic field applied to a laser with external mirrors and Brewster-angle windows will produce the σ^+ and σ^- circularly polarized beams within the discharge tube. On passing through the Brewster-angle windows, the electric vector perpendicular to the plane of incidence is partially reflected, and the emerging beam is elliptically polarized. With no laser excitation, the perpendicular field component would be lost rapidly in the optical cavity. With laser excitation, the loss for the perpendicular component due to window reflection is large enough to prevent laser oscillation in this field component. The contribution to the perpendicular field component per pass will be small, resulting in an output made up of two linearly polarized beams, one at the σ^+ frequency and one at the σ^- frequency.

Mirror Configuration

The mirror configuration presents no special problems beyond those already discussed in the chapter on physical principles in operating a laser with an axial magnetic field. This statement is made with regard to mirror shape--confocal, hemispherical, etc., and the mirror location, whether inside or outside the discharge tube. Mirror separation does present certain problems which will be discussed next under

the topic "frequency pulling." Mirror reflectance, which determines the Q of the optical cavity, also affects frequency pulling.

Frequency Pulling

Frequency pulling is a familiar phenomenon. In the case of two mechanical oscillators moderately to strongly coupled without buffering, when one is tuned rather closely to the frequency of the other, the two will tend to lock and oscillate at one frequency. A strongly tuned cavity will pull the frequency of a microwave oscillator if the two are tuned near the same frequency. The laser, with two resonant systems, exhibits frequency pulling also. The two systems are: the assembly of excited neon atoms, which are radiating by stimulated emission; and the optical cavity, which will support an integral or half-integral number of wave lengths.

If two similar resonant systems, A and B, with quality factors Q_A and Q_B, tuned to slightly different frequencies f_A and f_B, are coupled together, the combined resonant frequency, f_O, will be approximately $(f_A + f_B)/2$. If Q_A and Q_B are not similar, then for Q_A greater than Q_B, f_O will be closer to f_A than to f_B. A first approximation can be made by letting the "willingness to change frequency" be inversely proportional to the Q or

$$Q_A (f_O - f_A) = -(f_O - f_B) Q_B \qquad 17.$$

This is similar to the resultant gain of two tuned amplifiers whose individual gains are

$$A_A = A_{A_0} \frac{1}{1 + jQ(\frac{\omega}{\omega_A} - \frac{\omega_A}{\omega})} \qquad 18.$$

$$A_B = A_{B_0} \frac{1}{1 + jQ_B(\frac{\omega}{\omega_B} - \frac{\omega_B}{\omega})} \qquad 19.$$

The total gain is

$$A_t = A_A A_B = A_{A_0} A_{B_0} \frac{1}{1+jQ_A(\frac{\omega}{\omega_A} - \frac{\omega_A}{\omega})} \frac{1}{1+jQ_B(\frac{\omega}{\omega_B} - \frac{\omega_B}{\omega})} \qquad 20.$$

The imaginary component vanishes at the system resonant frequency:

$$j(Q_A(\frac{\omega}{\omega_A} - \frac{\omega_A}{\omega}) + Q_B(\frac{\omega}{\omega_B} - \frac{\omega_B}{\omega})) = 0$$

or

$$Q_A \frac{(\omega_0 - \omega_A)(\omega_0 + \omega_A)}{\omega_A \omega_0} = -Q_B \frac{(\omega_0 - \omega_B)(\omega_0 + \omega_B)}{\omega_B \omega_0} \qquad 21.$$

For ω_A approximately equal to ω_B,

$$\omega_A \omega_0 = \omega_B \omega_0 \qquad 22.$$

and

$$\omega_0 + \omega_A \approx \omega_0 + \omega_B \qquad 23.$$

Then

$$Q_A(\omega_0 - \omega_A) \approx -Q_B(\omega_0 - \omega_B) \qquad 24.$$

which is the same as equation 17.

In their article, Gordon, Zeiger, and Townes [10] gave the following expression for frequency pulling for a He-Ne laser, analogous to equation 24:

$$\frac{\nu_O - \nu_B}{\nu_O - \nu_C} = - \frac{\Delta\nu_B}{\Delta\nu_C} \qquad 25.$$

or

$$\nu_O = \nu_B + (\nu_C \Delta\nu_B - \nu_B \Delta\nu_B)/(\Delta\nu_B + \Delta\nu_C) \qquad 26.$$

where ν_O is the output frequency, ν_B is the neon transition frequency, $\Delta\nu_B$ is the half-width of the emission line of neon, ν_C is the cavity resonant frequency, and $\Delta\nu_C$ is the half-width of the cavity modes. This equation has also been derived by Bennett [11]. For example, if the cavity is initially tuned to the center of the neon line ($\nu_C = \nu_B$), the second term on the right will be zero. If now the cavity is tuned to a higher frequency, the amount of the frequency increase will not be $\nu_C - \nu_B$, but rather

$$(\nu_C - \nu_B) \frac{\Delta\nu_B}{(\Delta\nu_C + \Delta\nu_B)} \quad .$$

The nominal frequency of the neon transition and its bandwidth or line-width are constants. The cavity frequency is a function of the mirror separation, and the cavity Q is a function of the mirror reflectance. The neon bandwidth is approximately 1000 mcps, due mainly to Doppler broadening. At these wavelengths the cavity has a resonant point every 120 mcps for 125 cm. mirror separation. It was shown in Figure 2. on page 11 that for confocal mirrors of

125 cm. focal length, separated to 128 cm., that a point 2 mm. from the center of one mirror is 750 Å closer to the other mirror center than is the center of this mirror. This is a very large operational lattitude. The mirror reflectance is such that one per cent of the energy is lost per pass, giving Q of approximately 100. This is a bandwidth of 1.2 mcps, or a line half-width of 0.6 mcps. Frequency pulling may be calculated using these values; it may be more accurately calculated using known values for the particular equipment. The large operational lattitude mentioned above offers some relief from pulling, but only at the expense of having the beam wander about on the mirror. This is unlikely because the mirrors are focused. Usually different modes occupy different parts of the mirror. Consequently, a large expected shift in frequency due to the Zeeman effect in the presence of a magnetic field becomes, in actuality, a small shift, due to the frequency pulling of the cavity.

The frequency pulling expected in the laser used in this experimental study will now be calculated. Beginning with the equation for frequency pulling, 25 , the frequency difference between the σ^+ and σ^- beams will be calculated.

$$\nu_O = \frac{(\nu_B \Delta\nu_C + \Delta\nu_B \nu_C)}{(\Delta\nu_B + \Delta\nu_C)}$$

Let

$$\Delta\nu_B = \Delta\nu_C + \varepsilon$$

$$\nu_O = \frac{[(\nu_C + \varepsilon)\Delta\nu_C + \Delta\nu_B\nu_C]}{(\Delta\nu_B + \Delta\nu_C)}$$

$$= \nu_C + \frac{\varepsilon\Delta\nu_C}{\Delta\nu_B + \Delta\nu_C}$$

where ν_O is beam frequency, ν_B is neon line center frequency, $\Delta\nu_B$ is neon line width, ν_C is cavity center frequency, and $\Delta\nu_C$ is cavity bandwidth. Since the cavity remains tuned to the zero magnetic field beam frequency, ε is the frequency shift produced by the Zeeman effect, or the frequency difference between the σ^{+} and π beams. Due to frequency pulling, however, the expected observed difference is

$$\nu_O - \nu_C = \frac{\varepsilon\Delta\nu_C}{\Delta\nu_B + \Delta\nu_C}$$

The bandwidth $\Delta\nu_C$ of the optical cavity may be determined by considering the Q_c, or quality factor, and the resonant frequency increments of the cavity.

$$Q_c = \frac{\text{energy stored}}{\text{energy dissipated}} \text{ per cycle}$$

Dielectric mirrors of reflectance R will reflect R per cent of the E vector of the light (and consequently R per cent of the H vector) and transmit (100 - R) per cent. Power is proportional to the square of the magnitude of the E vector. The expression for Q_c may be written as

$$Q_c = \frac{R^2}{(100 - R)^2}$$

where R is given in percentage. With 99 per cent reflectance mirrors, Q_c is $(99/1)^2$ or approximately 10^4.

The resonant frequency increments may be determined by the number of integral or half-integral standing waves the cavity will support. Let n be the number of half wavelengths supported in the cavity, λ_1 the wavelength, and f_1 the corresponding frequency. The n + 1 will represent the number of half wavelengths supported in the cavity for a slightly different frequency, and f_2 the corresponding frequency. The mirror separation used is 1.28 meters. Then

$$n = \frac{1.28}{\lambda_1} = \frac{1.28}{\frac{3\times10^8}{2f_1}} = \frac{2.56f_1}{3\times10^8}$$

$$n + 1 = \frac{2.56f_2}{3\times10^8}$$

$$f_1 - f_2 = \frac{3\times10^8}{2.56} = 117 \times 10^6 \text{ cps}$$

The approximate response of the cavity is shown below.

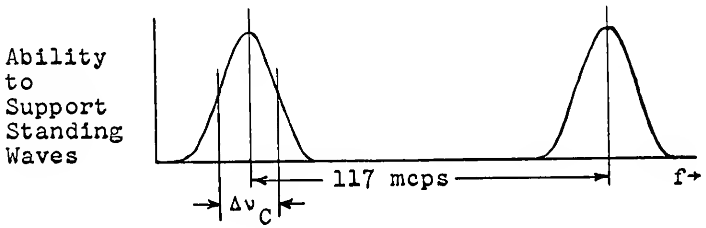

Figure 10. Response of Cavity

Based on the calculated Q_c and the axial mode separation, $\Delta\nu_C$ is $117\times10^6/Q_c$, or 11,700 cps.

Doppler broadening of the neon line amounts to 500 to

1000 mcps. Using the latter figure, $\Delta\nu_B = 10^9$. For $H = 10$ gauss and $g_J = 1.3$,

$$\epsilon = 1.4\times1.3\times10\times10^6$$
$$= 1.82\times10^7 \text{cps}$$

The frequency separation is

$$\nu_O - \nu_C = \frac{1.82\times10^7\times1.17\times10^4}{10^9+1.17\times10^4} = 210 \text{ cps.}$$

The calculated frequency separation between the σ^+ and σ^- beams is 420 cps, using a Doppler broadening of 1000 mcps, and 840 cps, for a Doppler broadening of 500 mcps. Magnetic field intensities from 0 to 70 gauss were used in the experiments so that the audio range would be covered.

Four Experiments

Three experiments have been described in the literature in which frequency pulling is studied. In two of these, the Zeeman effect is studied. Each of the first three experiments to be described was performed with the helium-neon laser operating on the 11,522 Å line, the laser being equipped with internal plane mirrors. Bennett [11] described an experiment where frequency pulling is measured. Approximate expressions to account for this pulling were derived. He did not deal with frequency shifts and consequent pulling due to the Zeeman effect, but with pulling due to the cavity, the gaseous medium in the cavity, and

the population levels of the excited gas.

The second, by Statz, Paananen, and Koster [5], was an experiment to determine the Zeeman effect. They used a linear polarizer to convert the circularly polarized waves to linearly polarized waves of varying amplitude which were then detected with an infrared phototube. The output with the earth's magnetic field parallel to the laser tube was 1050 cps, indicating that the σ^+ and σ^- rays were rotating in opposite directions at the rate of 525 revolutions per second. Assuming the field to be 0.5 gauss, they calculated a rotation of 300 rps. With an imposed field of one gauss, they calculated a rotation of 610 rps and measured 625 rps.

Culshaw, Kennelaud, and Lopez [12] measured the Zeeman effect superimposed on the 120 mcps beat note detected between oscillations in adjacent cavity modes. They inserted a Nicol prism to polarize the output wave and detected it with an infrared phototube. Both a 4 gauss perpendicular field and a 30 gauss axial field were used in the experiment. With the 30 gauss field, a modulation of 80 kcps was measured; a modulation of 130 kcps was calculated. This calculation included frequency pulling. These results compare favorably with those of Statz, et al.[5].

The last experiment to be discussed, performed by Kiss [13],deals with the Zeeman effect in the $CaF_2:Dy^{2+}$ solid state laser. This laser is photon exicted or light pumped and is operated at 27°K. The optical cavity consists of

high reflectance mirrors deposited on the ends of crystals, which are spherical. Small magnetic fields up to 80 gauss and large fields of 10,000 gauss were used. The results were as follows: the σ^+, π, and σ^- beam components were observed in the axial direction. A separation of the axial components of 150,000 mcps was observed with the use of a 10,000 gauss magnetic field. Using small fields, frequency modulation was obtained with cavities having a low Q and amplitude modulation with cavities having a high Q. The magnet system used homogenous and inhomogenous fields.

The Receiver

The frequency modulation receiver used in the present experiments employs a photomultiplier tube for the first detector stage. This tube is sensitive to instantaneous variations in incident light [10, 11, 12, 14] such as the beat or difference frequency between the σ rays. The output signal from the photomultiplier is amplified, then demodulated in an f-m detector to obtain the original signal.

Caddes and McMurtry [15] discuss photodetectors, giving a conversion equation as follows:

$$I_o = P_{light} \frac{\eta e}{h\nu}$$

where P_{light} is average light input power, η is quantum efficiency of the photon-electron conversion, e is electron charge, h is Planck's constant and ν is light frequency.

The magnitude of the output current is proportional to the square of the input light vector. For an input consisting of the σ^+ and σ^- beams,

$$\begin{aligned} I_o &= k(A \cos \omega_1 t + B \cos \omega_2 t)^2 \\ &= A^2 \cos^2 \omega_1 t + 2AB \cos \omega_1 t \cos \omega_2 t + B^2 \cos^2 \omega_2 t \\ &= A^2 \cos^2 \omega_1 t + B^2 \cos^2 \omega_2 t + AB(\cos(\omega_1 + \omega_2)t \\ &\qquad + \cos(\omega_1 - \omega_2)t) \end{aligned}$$

where k is a constant of proportionality, A is the magnitude of the E vector of σ^+, ω_1 is the frequency of σ^+, B is the magnitude of the E vector of σ^-, and ω_2 is the frequency of σ^-. If σ^+ and σ^- differ by a few hundred to a few thousand cycles per second, the difference in frequency will occur in the audio range. Let there be two axial modes of oscillation, identified as Beam 1 and Beam 2. For Beam 1, containing σ_1^+ and σ_1^-, separated 117 mcps from Beam 2, σ_2^+ and σ_2^-,

$$\begin{aligned} I_o = k(&A_1 \cos \omega_{11} t + B_1 \cos \omega_{12} t + A_2 \cos \omega_{21} t \\ &+ B_2 \cos \omega_{22} t) \end{aligned}$$

where k is a constant of proportionality, A_1 and ω_{11} are magnitude and frequency of E vector of σ_1^+, B_1 and ω_{12} of σ_1^-, A_2 and ω_{21} of σ_2^+, and B_2 and ω_{22} of σ_2^-. The σ^+ and σ^- separations will be approximately the same for Beams 1 and 2. If this separation is in the audio range of frequencies, then I_o will contain this audio frequency, the 117 mcps frequency, and sidebands separated from the 117 mcps component by the audio frequency. If

$$\frac{1}{2\pi}(\omega_{11} - \omega_{12}) = f_A$$

where f_A is an audio frequency, then I_o contains f_A, 117 mcps, 117,000,000 $\pm$ f_A cps, and others. The signal in frequency modulated form is contained in f_A.

IV

THE EXPERIMENTAL STUDY

The experimental study was conducted from July, 1963, to June, 1965. At that time, there were no gas lasers in the College of Engineering. Part of the time was spent building associated laser equipment, building laser discharge tubes, and making mirrors. The associated equipment will be discussed under Details of the Experiment. Several laser discharge tubes were built. These consisted of Pyrex tubes, usually thirty-six inches long and six to eight millimeters inside diameter, supported on end pieces. The end pieces were metal cups or fittings with windows, mounted on a sturdy base. A fitting at one end of the tube had a connection to the vacuum pump and the gas-filling apparatus. Several means of sealing the windows and the tube to the end pieces were used at different times, including vacuum wax, O-rings, and tin-indium glass to metal solder. These sealing systems allowed the tube, but not the end pieces, to be baked out.

Some plane mirrors were made on flat glass substrates using aluminum, and later, silver. The high reflectivity of magnesium made it attractive as a mirror coating, but the vacuum obtained in the evaporator used was inadequate for

giving good quality mirrors. The magnesium gettered the atmosphere of the bell jar, and the deposition was a combination of magnesium oxide and magnesium salts. At this point, multiple dielectric mirrors of confocal design were purchased from Optics Technology, Inc. These mirrors were fitted to the laboratory laser and a number of unsuccessful attempts to obtain laser action were made.

The gas filling apparatus consisted of a helium tank, a neon flask, a mercury manometer built for the laboratory, valves, and a thermocouple gauge. After evacuation, the laser tubes were filled with neon and then with helium to a final pressure of 0.5 torr to 1.0 torr. The gas composition was varied from pure neon to one part neon to ten parts helium. Windows perpendicular to the axis and Brewster-angle windows were tried. No evidence of laser action was observed with these tubes. It is believed that the lack of laser action may be attributed to windows which were barely of laser quality, to outgassing of the tube, and to impurities in the gases (which were not of spectroscopic grade). In the last stage of this work, the windows were checked in the optical cavity of an operating laser and found to be below laser quality.

Two commercially assembled laser tubes, PEK LT-11 and LT-12 were obtained and mounted on a previously constructed base. The PEK LT-11 and LT-12 have the gas mixture of helium and neon sealed in, are forty-seven inches over the Brewster-

angle windows, and have an inside diameter of six millimeters. No difficulties were experienced in obtaining laser action.

For later experiments, another laser discharge tube was built in the laboratory. This laser discharge tube was constructed with internal mirrors and windows normal to the beam. Mirror mounts were constructed which employed bellows to allow for mirror alignment adjustments. The Optics Technology mirrors were placed in the bellows mount with tin-indium solder. A connection was provided in one mount for the gas-filling apparatus linkage. A drawing of the basic unit appears on the next page in Figure 11.

The evacuation and back-filling equipment represents another change from the original experiments. A laser mixture of helium and neon, premixed in a one to seven ratio was obtained from the Linde Company. Evacuation to 10^{-6} torr (10^{-7} torr at the pump) used first a mechanical pump and then an ion pump, followed by heat gun bakeout of tubulation and discharge tube, but not mirror mounts. Then, gas was admitted through a leak valve into the tube to a pressure of about one torr. Laser action was easily obtained over a range of pressures near one torr.

Details of the Experiment

The large quantity of support equipment necessary for a laser experiment was in part built for the experiment and

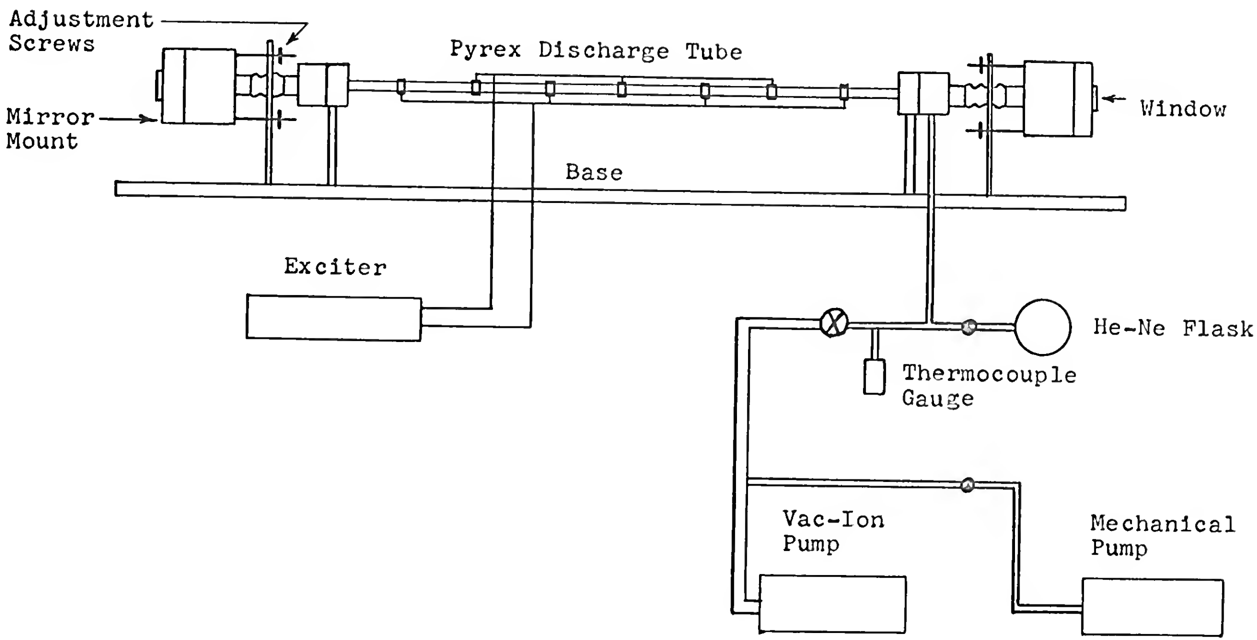

Figure 11. Basic Internal Mirror Laser

modified from equipment already in the laboratory.

Excitation System

This system consists of a radio-frequency exciter, matching network, and excitation electrodes, as shown in Figure 12. The exciter includes a 14.4 mcps driver and an amplifier. The amplifier uses three 807 tubes connected in parallel and has independently variable plate and screen grid power supplies. The system operates in a shielded design to minimize radiation. The amplifier is loop-coupled to a tank circuit in which the capacitance is made up largely of the capacitance in the electrode structure mounted on the laser tube. Several structures were tried; the final design consists of alternate ground and high voltage electrodes wrapped partly around the tube and connected to the longitudinal ground or high voltage buss. The busses are separated by ceramic spacers and the whole structure is hung from the tube. There are five high-voltage electrodes and six ground electrodes.

The Modulation System

Several modulation magnets were constructed for the experiment in order that the direction of the externally applied magnetic field through the laser might be varied. The LT-11 tube was fitted with a solenoid three inches in diameter, forty inches long, and wound with two forty-turn windings. Calculations and measurements showed that this

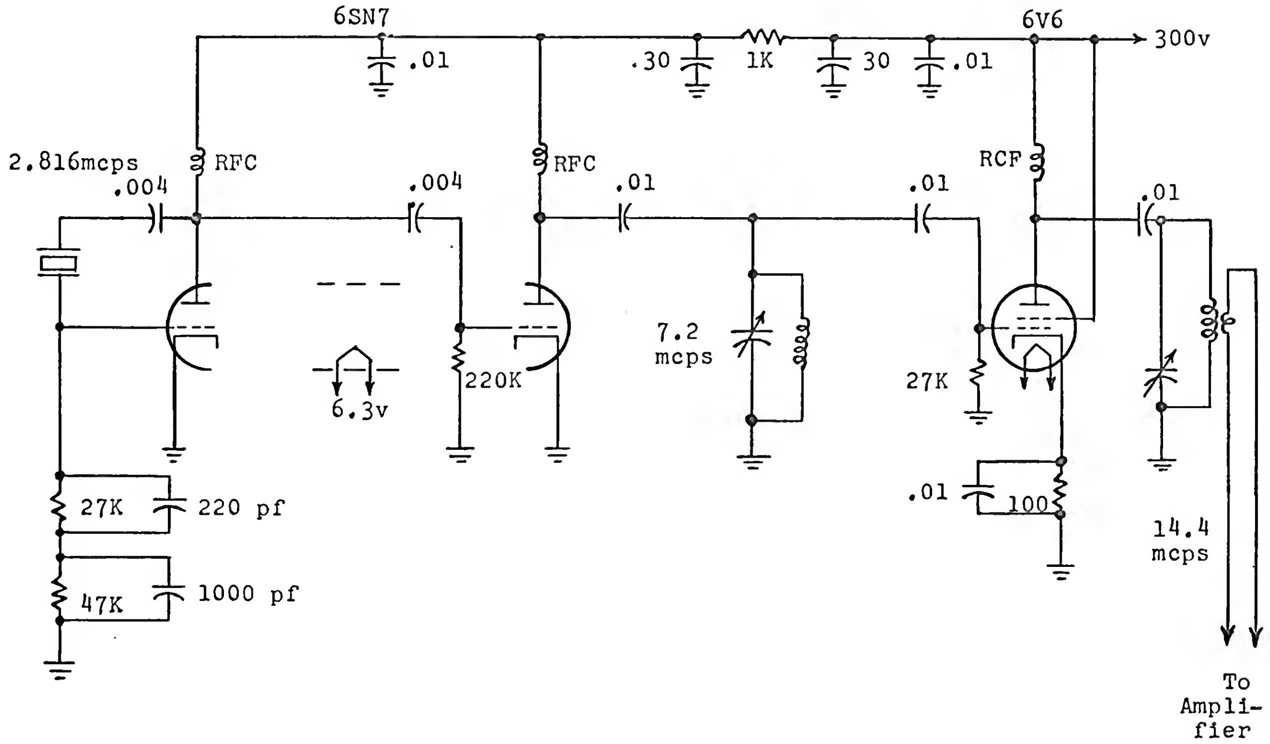

Figure 12. Exciter Diagram

(a) Radio Frequency Driver

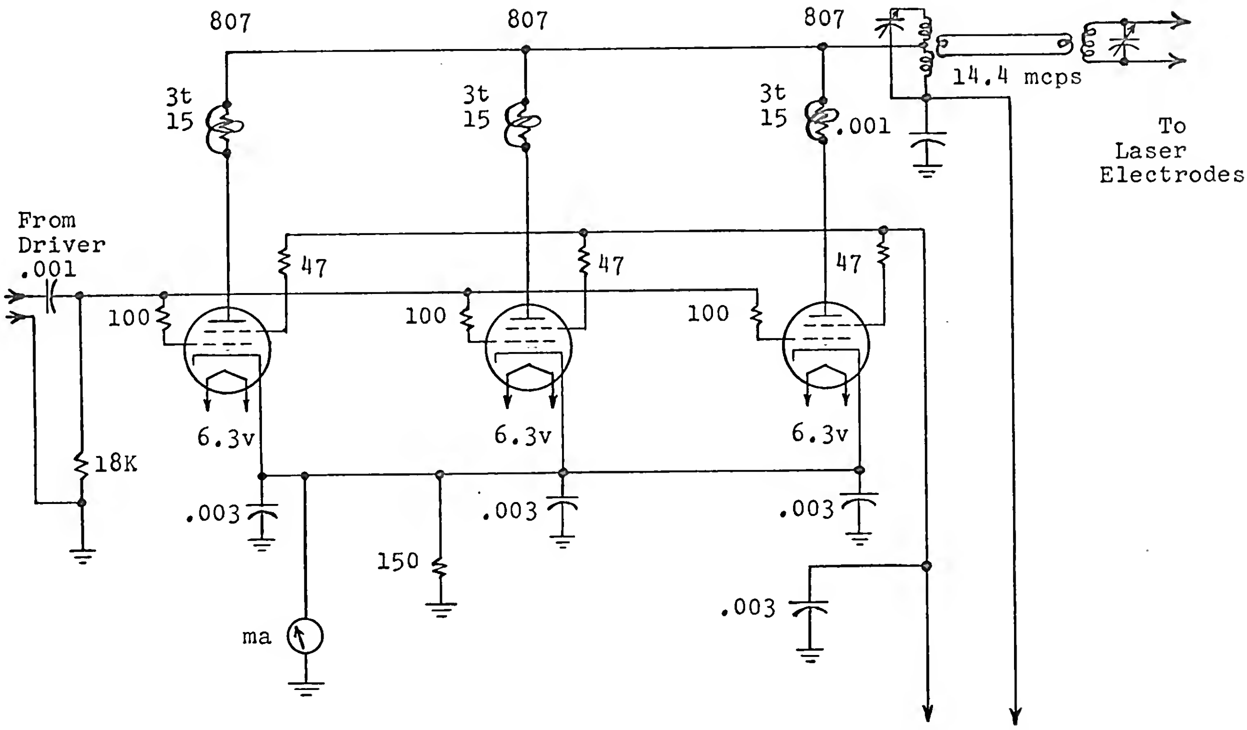

Figure 12. Exciter Diagram

(b) Radio Frequency Amplifier

solenoid produced an axial magnetic field with less than ±10 per cent variation of field strength over the length of the discharge.

For the LT-12 tube, a pair of rectangular coils about two and one half inches by forty inches, each having a total of eighty turns were constructed. These were placed one on each side of the tube with about three inches separation and connected so that the fields produced were in the same direction. Measurements showed a variation in this transverse field of less than ±8 per cent.

The rectangular coils described above were used with the internal mirror laser. At the field strengths necessary for observing the Zeeman effect, the coils heated rapidly. A similar set of rectangular coils three and one-half inches by forty inches were built, each having approximately 2500 turns. These were placed one on each side of the discharge tube with two and one-half inches separation. Measurements again indicated a variation in transverse field strength of less than ±8 per cent.

The Receiver System

The optical portion of the receiver consists of two first-surface glass dielectric reflectors (reflection taking place at the air-glass boundary) set at the polarizing angle, and a photomultiplier tube. The reflectors remove the component of light which has the E vector in the plane of incidence, this being the π component. The σ components

are transmitted. The photomultiplier cathode is a square law detector which has all the original, sum, and difference frequencies in its output. Due to the low-pass nature of the electron multiplier section of the tube, the electrical output is made up solely of the lower difference frequencies.

The output frequencies include the axial mode beat frequencies in the 115 to 125 mcps spectrum, recoverable with a conventional receiver which tunes to this range, the frequency difference between the σ^+ and σ^- rays in the audio range when a magnetic field is applied, and the beat frequencies between the transverse modes in the audio range if more than one exists.

The f-m receiver used consisted of a wide-band amplifier 0 - 20 mcps, driving a monostable vibrator. The multivibrator output passed through a diode gate and into a low pass filter. The filter output drives an audio type amplifier and speaker. This is a type of frequency counter in which the output voltage varies as the input frequency which controls the repetition rate of the multivibrator. The wide-band amplifier and multivibrator used are part of the circuitry of a Tektronix Model 541 oscilliscope. The receiver diagram is shown in Figure 13 on page 48 and the low-pass filter schematic and response curve in Figure 14 on page 49.

Preliminary Tests

The LT-11 laser was used first with an exciter of low

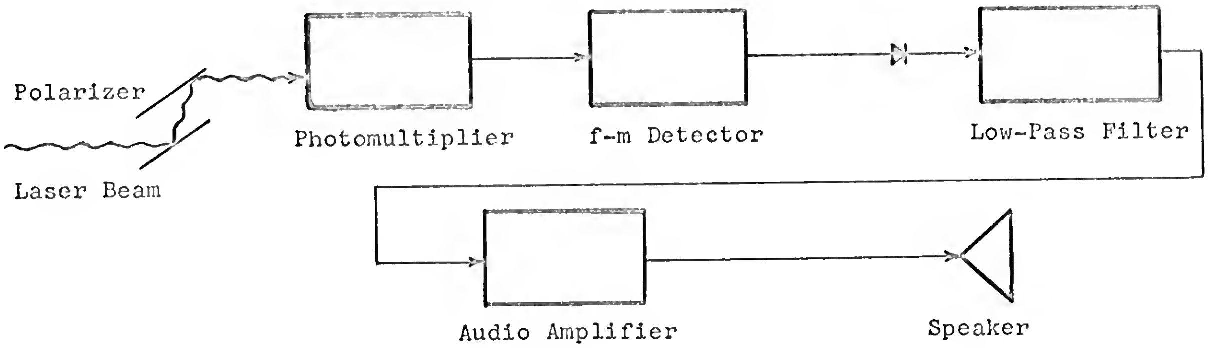

Figure 13. Receiver System

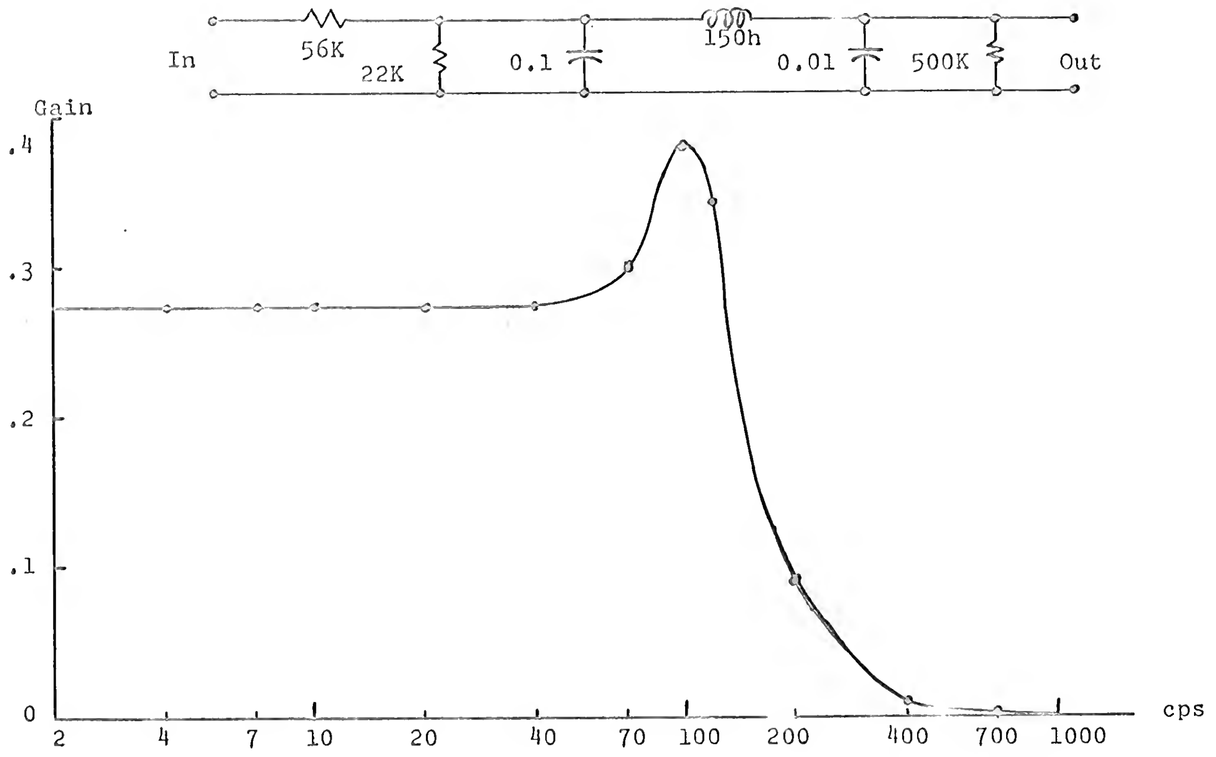

Figure 14. Filter Network and Response

power. It provided sufficient excitation for single transverse mode lasing at 50 to 60 watts and multiple transverse mode lasing at 70 to 80 watts. With ambient dust in the air, the beam intensity was observed to be much greater in the cavity than outside the cavity. This is normal, since the reflectivity quoted for the mirrors was 99.5 per cent. The transmission was probably 0.2 per cent. The ratio of reflection to transmission was probably 500 to 1.

Tolerance of mirror alignment was next observed. With 80 watts excitation, lasing was maintained over a range of one-half turn of the adjusting screw. This corresponds to a total angular movement of the mirror of one-third degree, or a deviation from alignment center of ten minutes. At the same time, another beam with brightness of from 10 to 50 per cent of the main beam was observed. This beam reflected from the Brewster-angle window at an angle apparently equal to the angle of incidence. The spot size, observed on the ceiling, indicated that this was a reflected beam and not just light scattering from imperfections or dust on the window. The intensity of the beam transmitted through the mirror is approximately 0.2 per cent of that of the internal beam. Therefore, the reflected beam is from 0.02 per cent to 0.1 per cent of the intensity of the beam within the cavity. This indicates that the beam, without a magnetic field, is essentially linearly polarized; the reflection may come from a slight deviation from linear polarization in the

discharge tube, slight non-parallelism of the Brewster-angle windows, or from slight angular displacement of the polarization by the confocal mirrors.

A large glass cylinder with glass ends was filled with benzene to see if the beam could be observed as it passed through. The benzene did not diffuse the beam. It could be observed if a diffusing material were suspended in the benzene. Tap water gave no results either. The beam was visible as it passed through a jar filled with smoke.

A photographic slide was made on Kodachrome II film. The beam intensity was measured with a light meter, the diaphragm and shutter speed were set and the picture taken. The result was a completely over-exposed spot in the center of an otherwise black slide. The fact that the camera diaphragm opening has no effect on the intensity of light incident on the film was overlooked; over-exposure could have been avoided only by increasing the shutter speed.

V

MEASUREMENTS AND RESULTS

The first experiments were made with the LT-11 laser tube and the axial field solenoid. When several transverse modes were present, the beat frequencies between them were detected in the audio range. Decreasing of the exciter power and realignment of the mirrors returned the system to single transverse mode operation and the beat frequency output ceased. The axial transverse mode beats were detected at 117 mcps using a narrow band all-frequency receiver. With increased exciter power, the multiple transverse mode beats appeared as modulation on the axial mode beats. Next the magnetic field was applied in the range of 0 to 70 gauss. The beat frequency between the σ^+ and σ^- rays could not be found. Calculations for frequency pulling were made, indicating that an output should be observable in the 10 to 20 gauss range. However, the Zeeman effect did not go entirely unnoticed. A beam disturbance detected electrically as an impulse was observed each time the magnetic field was applied or removed. This is possibly caused by a change in ν_B due to the Zeeman effect which resulted in sufficient detuning to cause one of the axial modes to cease or begin to oscillate. Under conditions of low exciter power and slight mirror misalignment, lasing would occur only if the magnetic

field were present, again possibly due to a change in ν_B due to the Zeeman effect.

Due to the effect of the Brewster-angle windows, the beam remained linearly polarized throughout the range of the magnetic fields used. This was determined using double dielectric reflectors of the type mentioned in the discussion on the receiver system mounted at each end of the laser in the paths of the output beams.

The LT-12 tube was next used with transverse magnetic field coils. With no magnetic field applied, the results of the experiments for the transverse mode beats and the axial mode beats were the same as those obtained with the LT-11 tube. The transverse magnetic field was applied successively in two directions, first to pass the σ rays through the Brewster-angle windows unreflected, and second to pass the π ray unreflected. In each experiment, the Zeeman effect was not observed. Electrical impulses in the output were obtained upon sudden application or removal of the field, but the beat frequency between the σ^+ and σ^- rays with the field applied was not detected with field strengths up to 50 gauss.

The internal mirror laser described on page 41 was used next, noting that careful attention to good vacuum techniques was necessary to assure reliable operation. The transverse mode beat frequencies again could be obtained and removed by exciter power control and mirror adjust-

ment. The axial mode beats were obtained at 121 mcps, the change due to a reduced mirror separation. The Zeeman effect was observed with field strengths of 50 to 70 gauss. The need for higher magnetic fields was anticipated due to the nature of the laser, the Q of the cavity should be greater than that of the earlier systems as this system does not contain Brewster-angle windows. The Zeeman splitting did not run smoothly up from 0 gauss, but appeared suddenly in the 400 to 800 cps range with about 50 gauss applied. The Zeeman effect was obtained with single transverse mode laser operation. The frequency output, or amount of splitting, depends both on the strength of the applied field and the exciter power level. This splitting dependency has been reported by Statz, et al.[5].

With a field level of 60 gauss and a low exciter level, a splitting of the line of 100 cps was obtained and used as a carrier frequency. The field was then modulated over a range of 20 to 200 cps. The frequency modulated signal was detected over this same range of signal frequencies using the receiver. The inductance of the transverse magnetic coils and the low-pass characteristics of the receiver filter precluded the use of higher modulation frequencies. It is interesting to note that photomultiplier alignment was not critical for detection of the Zeeman effect. Parallelism between the beam and a vector normal to the photocathode of within 2 to 3 degrees was adequate.

VI

SUMMARY AND CONCLUSIONS

At the beginning of this experimental research, use of only the LT-11 laser tube and axial field solenoid was planned. The negative results obtained in this experiment and later with the LT-12 laser experiments made it necessary to enlarge the scope of this experimental study twice to achieve positive results. The conclusions based on the LT-11 and the LT-12 laser tubes will be given first.

At no time was a signal detected which would indicate frequency modulation by means of the Zeeman effect with the external mirror lasers. The three measurements concerned the different orientations between beam polarization, $\underline{E}$, and the magnetic field $\underline{H}_f$. These are shown below in Figure 15.

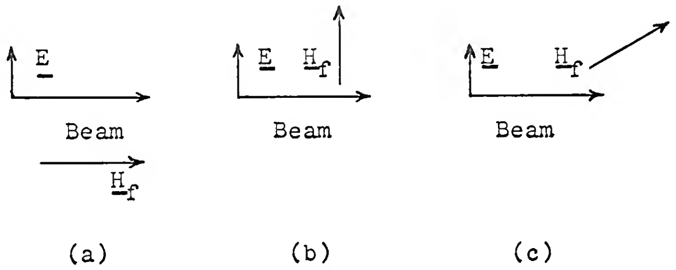

Figure 15. Magnetic Field Beam Orientation Polarizations

The first measurement was made according to Figure 15(a). The Zeeman effect indicates that the beam will contain the σ^+ and σ^- rays which will be circularly polarized in opposite directions. The optical cavity contains two Brewster-angle windows which are thought to prevent amplification of a circularly polarized wave. This was found to be the case. No beam was found with the electric vector perpendicular to the plane of incidence. Prohibition of circular polarization may prevent the frequency shift due to the Zeeman effect.

The second measurement was made according to Figure 15 (b). Here, the beam should contain the σ^+ and σ^- components plane polarized in the plane of incidence. Again, no signal was found, apparently because of the strong effects of the plane polarization, or perhaps because of much greater frequency pulling that that believed to be present.

The third measurement was made according to Figure 15(c). There, the beam should contain only the π component. Again, no σ components were detected.

The axial modes, spaced every 117 mcps, were detected. With more intense beams, which permitted laser operation in several transverse modes, audio frequency whistles and squeals were detected. These frequency differences between transverse modes are due to slight path length differences. It appears that the detector does operate properly.

Based on these observations and on the four experiments

in the section on the Zeeman effect frequency modulated laser, it is concluded that this laser structure with external mirrors and Brewster-angle windows cannot be frequency modulated using the Zeeman effect with magnetic fields from 0 to 50 gauss.

The Zeeman effect may be observed in spontaneous emission provided that the σ rays can reach the detector. In laser operation, the neon atom radiates downward from a higher energy level which is metastable. If the σ rays are discriminated against by the optical structure, specifically the Brewster-angle windows, there will not be enough gain to support laser action in the σ ray mode. Then there will be no σ rays to stimulate emission from those metastable atoms with $\mu_H \neq 0$.

The internal mirror laser does not contain any strong polarizer in the form of a Brewster-angle window. Outside the optical cavity, windows are used which are normal to the beam so that there is no polarizing influence there. The only polarizer which may be present, excluding the magnetic field, is a mirror imperfection, and this is not large. The Zeeman effect was observed repeatedly using the internal mirror laser and transverse magnetic fields in the range of 50 to 70 gauss with $\sigma^+ - \sigma^-$ frequency differences of approximately 1000 cps. The magnetic field strength was modulated directly with the signal. The signal was recovered from the frequency modulated light beam using the receiver.

It is noted that from the results of the frequency pulling equations, the Zeeman effect will be small, even in a laser cavity which will support circular polarization. Therefore the range of carrier frequencies and useful modulation frequencies will be small for easily achieved magnetic field strengths. Additionally, at a sufficiently high field strength, the σ^+ and σ^- lines may jump to the next axial mode, establishing an upper limit to the useful modulating frequency. By shortening the length of the optical cavity, the axial mode frequencies are raised.

Frequency modulation by the Zeeman effect does offer several important advantages. First, it is simple and economical. The magnet structure is simple, and modulating the magnetic current produces frequency modulation of the carrier, which is the difference between the σ^+ and σ^- rays. The system is less sensitive to vibration than a moving mirror system, and does not contain ADP or KDP crystals, which are expensive and which require high driving voltage. The polarizer may be mounted on the laser in the output beam path to lessen the alignment problem between transmitter and receiver. Since both the σ^+ and σ^- rays are transmitted, the receiver photomultiplier tube functions as the first detector of a superheterodyne receiver with the carrier and the local oscillator signals both coming from the transmitter. In the experiment, the corresponding intermediate frequency is centered at 1000 cps. With this

system, there is no need for a second laser to function as a local oscillator, eliminating what has been, up to now, a significant stability problem. Elimination of the second laser is an added economic factor.

From this research, it is concluded that frequency modulation by means of the Zeeman effect is practical only for narrow bandwidth applications, but offers significant advantages in that area. These advantages are simplicity and low cost of the modulator magnet, simple modulator electronics and receiver design which is no more complicated than f-m receivers at radio frequencies. As the modulator magnet does not come in contact with the discharge tube or optical system, the way is left open for combining this system with other systems. Further, the Zeeman effect is not only influenced by the Q of the optical cavity, but also by the nature of the polarizers within the cavity.

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BIOGRAPHICAL SKETCH

Rhett Truesdale George, Jr., was born on May 2, 1933, in Columbia, South Carolina. In June, 1951, he was graduated from Boys' High School in Anderson, South Carolina. In June, 1955, he received the degree of Bachelor of Science in Electrical Engineering from Duke University. He received the degree of Master of Science in Engineering from the University of Florida in 1956. From 1957 to 1961 and during the fall of 1962, he taught Electrical Engineering at Duke University. In the Fall of 1961, he enrolled in the Graduate School of the University of Florida and has pursued his work toward the degree of Doctor of Philosophy until the present time. From 1961 to 1963, he worked as a graduate assistant on the Ford Foundation program in the Department of Electrical Engineering. From September,1963, to August, 1964, he was on the Duke University advanced degree program for faculty. From September, 1964, to the present time, he has been teaching Electrical Engineering at Duke University.

Rhett Truesdale George, Jr., is married to the former Joanna Marie Huffer. He is a member of Sigma Xi, Phi Beta Kappa, Tau Beta Pi, Eta Kappa Nu, and Omicron Delta Kappa.

This dissertation was prepared under the direction of the chairman of the candidate's supervisory committee and has been approved by all members of the committee. It was submitted to the Dean of the College of Engineering and to the Graduate Council, and was approved as partial fulfillment of the requirements for the degree of Doctor of Philosophy.

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